Department of Energy National Petroleum Technology Office

Final Report

Work Performed Under Contract Task 03NT30429
Sub-Task 1:
Current Capabilities of Hydraulic Motors, Air/Nitrogen Motors, and Electric Downhole Motors
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1.0 Introduction

The purpose of this task is to investigate and identify the history and the state of the art capabilities of downhole motors related to small diameter coiled tube (CT) drilling and also to ultra-high speed drilling bits (up to 50,000 rpm) for small diameter holes less than 3-½ in. for CT drilling. The effort defines the operating conditions of the various types of downhole motors and their limitations; identifies the current research that is being conducted by service companies, universities, national laboratories and other research and development (R&D) organizations; and identifies continuing industry needs in the area of technology in addition to identifying key researchers and any current projects being conducted that would be applicable to the NETL-NPTO's microhole initiative.

In support of this task, an extensive search was conducted that included, but was not limited to, the internet, trade publications and trade journals to identify downhole motor manufacturers. This was followed by contacting downhole motor manufacturers and gathering literature on downhole motor capabilities and gathering any supporting information that might be valuable in evaluating their downhole motors. A literature search was conducted that included academic research, professional and technical papers, patents, professional periodicals, government research projects and technical manuals and publications from downhole motor manufacturers. The scope of this document includes all available information specific to manufacturers of 3-½ in. or smaller downhole motors, focusing on the manufacturers of the smallest available downhole motors. Of specific interest to the conclusion of this document is an assessment of the capabilities of the smallest downhole motors to drill small diameter holes and a recommendation on whether the current state of the art in downhole motors is mature or that more research and development needs to done.

2.0 Brief History of Coil Tubing and Summary of Downhole Motors

The operational concept of coiled tubing involves running a continuous string of small diameter tubing into a well to perform specific well operations without disturbing completion tubulars and equipment. When servicing is complete, the small diameter tubing is retrieved from the well and spooled onto a large reel for transport to and from work locations. (Reference #6)

Some of the many advantages of coiled tubing over conventional jointed tubing include timesavings, pumping flexibility, fluid placement, reduced formation damage and safety. Coiled tubing has been used within a number of intervention areas such as well cleaning, fishing and milling, zone isolation, stimulation and fracturing, sand control completions, flow management, plug and abandonment, and sidetracking and re-entry.

Modern coiled tubing has been around since the 1960's. But due to poor performance during its initial use, such as breakage of CT linkages, coiled tubing gained a poor reputation in the petroleum industry. Only in the last 10-15 years, due to increased reliability and performance improvement, has coiled tubing gathered greater acceptance.

As such, coiled tubing may eventually provide a method to greatly reduce the cost of drilling shallow and moderate depth holes for exploration, long-term monitoring and limited production.

Drilling motors as small as 1-in. in diameter are not new. Bits that bore a 1.175-in. hole to recover a 0.735-in. core are standard bits in a diamond-drilling handbook (Reference #11). These bits are run on drill rods with an outside diameter of 1.098-in., using a mining rotary drill. The mining drill has not found wide acceptance for drilling slim holes in oil field rocks for a number of reasons, including well control, low penetration rates, bit balling in deeper clays and shale, and depth limitations have limited the mining drills application in oil field drilling (Reference #2). To get to the smaller size of motor that is of relevance to the microhole initiative, CT drilling motors are of specific interest. CT downhole motors can range in size from 12-3/4 in. to as small as 1.2-in. Downhole motors can be made even smaller, but due to a number of reasons, including economic feasibility and narrow range of use, smaller motors have not been manufactured. Maurer Engineering and a Russian company were supposed to build a 1-in. motor for Los Alamos National Laboratory (LANL), but the work was never funded. The 1.2-in. motor has only been recently tested in thru tubing for scaling removal, and the slightly more common 1-½ in. motor has been primarily used for cleanout and scaling removal. The smallest downhole motor that is most commonly used today is the 1-11/16 in. downhole motor. This is mostly used in 2-7/8 in. pipe diameters for thru tubing activities in well intervention areas.

Los Alamos National Laboratory has done significant work, drilling small diameter holes using off the shelf equipment. They have had some success drilling small diameter holes as small as 1-3/4 in. down to depths of 800 ft. Based on their results; the small commercially available downhole motors, with their low weight on bit, are sufficient for drilling in soft formations. It is anticipated that they are insufficient to drill in harder formations that are to be expected during production drilling. LANL believes more research and development will need to be done to develop drilling motors designed to operate at low-flow (approximately 15-20 gpm) and high differential pressure as part of a larger drilling system that will be capable of drilling harder formations. This is necessary to, among other things, decrease the risk of washing out the hole during drilling. Typical commercially available downhole motors operate at high flow rates (40-45 gpm) and standard differential pressure. Single lobe motors have been more successful than multi-lobe motors (say four or five) due to the decreased flowrate through the motor.

3.0 Results and Findings

3.1 Motors

There are currently three types of downhole motor that are available for coiled tubing units. The three motor types are 1) hydraulic 2) compressible (i.e., air, nitrogen, foam, etc.) and 3) electric. Each motor type has its advantages and disadvantages. The downhole motor can generally be broken down into the following sections: the power

section, which is the primary component of the drilling motor, top sub, transmission assembly, a bearing assembly and a drive sub.

3.1.1 Hydraulic Motors

Description

The most common motor in use is the hydraulic positive displacement motor (PDM). The hydraulic PDM, using the Moineau principle, converts hydraulic energy provided by the drilling fluid into mechanical energy. The power section is responsible for the conversion of hydraulic energy to mechanical energy. The power section consists of the rotor and stator with the rotor the rotating part and the stator the stationary part. Drilling fluid pushed through the power section creates the necessary power for the drilling motor. These motors are the best suited for drilling due to their ability to provide high torque at low rotational speed.

Hydraulic PDMs have a number of drawbacks such as short motor run life (especially in small diameter holes), poor performance in high temperatures, limited choice of drilling media, and the need to compromise the fluids program between the drilling and formation requirements. This restricts the operational effectiveness of PDMs in many areas (Reference #7).

Current State of the Art

Currently there seems to be no technological or manufacturing limitations on producing downhole motors that are smaller than the most commonly used size of 1-11/16 in. Several downhole motor manufacturers have indicated that they can build a downhole motor as small as a 1-in., but there is no economic incentive and the use of such a small motor would be extremely limited. Roper Pumps has manufactured power sections and downhole motors as small as 1-1/2 in. as well as a 1.2-in. downhole motor for a client in Texas. The 1.2-in. downhole motor is only being used for scraping the inside lining of pipe, and there is no current literature available on the motor. The main reason that smaller downhole motors are not routinely manufactured is that there is no driver or need within the petroleum industry to build these smaller motors. The 1-1/2 in. motor is primarily used in thru tubing operations within a narrow scope of cleaning and scraping. These motors typically have a short life span, and would not be feasible for drilling due to the amount of duty-cycle that would be required of the motor plus the low dollar return from such a small motor. For drilling purposes, a 1-1/2 in. motor would need to provide 150-200 hours of operation, but could realistically only provide 20-50 hours. The larger 1-11/16 in. motor can routinely provide 50-100 hours of operation, if not more. Thus while there seems to be no current technological limitations on the actual building of a smaller downhole motor, there is a question whether a smaller downhole motor will be robust enough to handle the stress of well drilling, as well as whether it is economically viable due to a decreasing dollar return the smaller the motor becomes.

Research Trends

Current research in small downhole motors is relatively minor. No universities have been identified that are involved in small downhole motor research and development. Los

Alamos National Laboratory is the only national lab that has been identified that is doing work on micro borehole technology. Their research focuses on using off the shelf equipment and testing it in production drilling scenarios. There is currently not much demand for making smaller downhole motors than are currently available. Nor has there been an economic incentive identified that would spur such an R&D initiative. Manufacturers can build motors as small as 1-in., but there are no economics to precipitate their manufacture. A power section could be manufactured for such a small downhole motor, but it would more than likely not generate a high enough torque output to be feasible for production. It would be limited to a narrow range of thru tubing operations identified earlier, such as scale removal in a well. The current state of the art is considered to be sufficient by industry to address the petroleum industries' needs. The 1-11/16 in. motors are the most commonly used motors in thru tubing operations for pipe diameters of 2-7/8 in.

There are improvements that are currently being made to increase the performance of downhole motors and their versatility. One of the areas of enhancement is improving downhole motors to work in extremely high temperatures. Downhole temperatures are one of the limiting factors in the use of small downhole motors, resulting from the higher drilling speeds. The Rotech Group (which exclusively manufacture the MacDrill for Weatherford) and Roper Pumps are currently manufacturing or have manufactured small downhole motors that may work in temperatures up to 500 ºF and 465 ºF respectively. Improving on the capability of downhole motors to work in high temperature environments is an area of possible improvement.

Other areas of possible research and development would be in the improvement of motors in producing higher torque especially for the smaller downhole motors and in improving the downhole motors to increase drilling life and make them more versatile in using a diverse range of drilling fluids. As an example, oil based mud at higher temperature breaks down rubber, while water based mud causes less wear on the rubber. Small diameter motors are currently being tested as a means for perforating a well compared to conventional means. They are more likely to perforate a well farther out and thus may be able to extract oil more efficiently and easily. Development of downhole motors that are shorter in length is another possible area of improvement, especially in the power section. Power section manufacturers currently offer power sections that are smaller in size for downhole motors that are reduced length.

3.1.2 Air/Nitrogen/Foam (Compressible Fluid) Motors

Description

The second type of downhole motor used in the petroleum industry is the compressible fluid motor, or air motor as it is commonly referred to in industry. Instead of using hydraulic fluid to power the PDM, a compressible fluid is used. Compressible fluids include air, nitrogen, and foam. Downhole air motors have been used primarily in diameters greater than 3-in for a number of reasons. Until recently, compressible fluids such as air or nitrogen have resulted in poor motor performance during drilling operations. The main reason is that the smaller the motor, the less torque is produced,

especially in relation to hydraulic downhole motors. Also, when using hydraulic fluids for downhole motors, one of the key strengths is that the hydraulic fluid provides cooling to the bit. Compressible fluids such as air or nitrogen, while providing some cooling to the bit, do not provide enough to have a practical effect. Foam provides greater lubricity and cooling than either air or nitrogen, but doesn't provide the same cooling capabilities that a hydraulic motor does. The cost of a compressor of adequate size to drive the motor (usually requiring a 3-stage compressor and requiring a very high volume of gas) could be very expensive and large and thus could be a limiting factor. There is less control of the output associated with compressible fluids. Motors have a greater tendency to speed up and slow down, making them less reliable. Compressible fluid motors are more sensitive to stalling at low pressures. There are explosive decompression issues associated with using air and nitrogen. Air may produce an environment for explosion or burning. Also it is more difficult to remove cuttings from the hole using a compressible fluid, than with hydraulic motors.

Use of compressible fluids does however have some major benefits that make it a viable drilling option. The major advantage is that it is extremely successful in underbalanced drilling. The pressure when using a compressible fluid as a drilling fluid is less than the reservoir pressure. This helps prevent damage to the formation and thus increase productivity of the well. Another advantage is that compressible fluids such as air and nitrogen are more environmentally safe than drilling fluids composed of water, chemicals and other minerals. Air and nitrogen will not contaminate a formation while another drilling fluid could.

Current State of the Art

Recent improvements have been made that may make compressible fluid motors more feasible. As an example, Rotech's MacDrill comes in a size as small as 1-11/16-in., and can be run with any clean compressible fluid or non-compressible fluid. Weatherford has used nitrogen, which has produced positive results for them. The results with compressed air haven't been as successful due to oxidation, scaling and breaking off of components/materials. Weatherford has also been experimenting with tolerances in its rotors and stators to improve performance for using compressible fluids. Roper also manufactures power sections that can run more efficiently on compressible fluids such as air and foam starting in sizes as small as 1-11/16 in. R&M Energy Systems manufactures power sections as small as 2-7/8 in. for compressible fluids. They do not make smaller units because they feel there is no need in industry, but they could manufacture smaller units if a market existed.

Research Trends

Dr. Philip Johnson of the University of Alabama Chemical Engineering Department completed research a couple of years ago on a compact pneumatic turbine driven downhole motor to solve drilling problems such as the capability to steer the bit at a constant speed. The motors that were developed were of short length to allow maneuvering in boreholes with a large radius of curvature, and they allow continuous flow of air so hole cleaning is never abated. A spin-off from of this work was an investigation into special applications for turbo-machinery. Small, slow-speed were

studied that would provide enhanced motor life, allow salvage of waste heat, and supply safe engines for environments.

Other than the previous research that has been highlighted, improvements in air motors in terms of output and performance in higher temperature settings seems to be the main thrust within industry. This is mainly due to the benefits associated with use of compressible fluids in underbalanced drilling operations.

3.1.3 Electric Downhole Motors

Description

The electric motor is controlled directly by the operator as commands are sent through the surface gear and computer whereas a PDM is controlled indirectly via variations in the mudflow. The electric motor allows complete, and direct, control of the motor. Speed may be increased or decreased with a joystick or set through a keyboard instruction. Hydraulic power is required solely for cuttings clearance. This provides for better control of the drilling process while allowing circulation flexibility. Another advantage of the electric drilling motor is the bottom hole assembly (BHA) is insensitive to aerated or energized drilling mediums. Air drilling may even be considered with the electric motor. This allows for the use of a full range of underbalanced drilling techniques. Conventional CTD motors are not capable of the full range of underbalanced drilling techniques because of reduction of performance associated with some of the techniques (Reference #20).

There are a number of difficulties associated with electric motors. One problem associated with electrical motors is a low starting torque. There have also been difficulties associated with plugging of the pump used for pumping production fluids out of the well and the inability to restart afterwards. Another difficulty is both motor and electrical shorts during operation. Rotating seals provide the primary protection for motor electrical wiring. Recent attempts to integrate electric motors into a rotary drilling assembly have had limited success, mainly due to the difficulties of providing a high capacity electric link to the downhole drilling assembly.

Current State of the Art

The idea of electric drilling is not new. During the last 100 years, experts from the United States, Germany, France, Austria/Hungary, Romania, and Russia have tried to develop drilling machines with electric motors (Reference #10). Canadian Advanced Inc., the only manufacturer of electric downhole motors in Canada, manufactures motors ranging in size from 4-1/2 in. to 8-5/8 inch OD. XL Technology is currently testing a new type of electric downhole motor that is 3-1/8 in. ***The new electric motor is an encapsulated permanent magnet motor instead of being an induction motor. The new electric motor is expected to address the major weaknesses of the current electric motor. It is expected to have high starting torque compared to the starting torque of current electric motors. The speed should be able to be ramped up at any required rate. The motor is expected to be totally encapsulated, with no rotating seals, no motor oil, and no pressure compensation chamber. (Company Confidential information. Not for public***

distribution outside of NPTO). XL Technology has completed the second phase and is in the third part of the three-phase project.

The Former Soviet Union (FSU) in particular has extensive experience with electric downhole motors. The FSU developed its first efficient electric downhole motor for deep drilling between 1937 and 1940. Today, commercial electric downhole motors range in size from 5-in. OD to roughly 11-1/2 in. OD in Russia, and show considerable potential for deep, directional, horizontal and multilateral drilling. Recent studies in Russia show positive prospects for development of 3 to 4-in. diameter electric drills for CTD applications. (Reference #10)

Research Trends

As mentioned in the current state of the art, the only research that may be applicable is the work being done by XL Technology using the 3-1/8 in. electric motor. XL Technology is testing the electric motor for its effectiveness and performance. Any future research will more than likely focus on the results of the ongoing work. ***XL Technology has the capability to manufacture smaller motors, but they would be generally used in logging type tools, which is not a market they are currently interested in pursuing. (Company Confidential information. Not for public distribution outside of NPTO).*** All other electric motors that have been identified are larger in size and wouldn't be directly adaptable to CT operations for the microhole initiative.

3.1.4 Power Section Manufacturers

The power section is the main component of the hydraulic and air drilling motor. It is responsible for converting hydraulic energy created by the drilling fluid into mechanical energy. The output is rotational speed and torque. The basic components of the power section are the rotor and the stator. The rotor is a polished metal spiral that rotates, while the stator is the stationary portion. The stator consists of a steel tube with an elastomer inside. There have been some variations to this model. The Rotech Group has manufactured a stator that is made of stainless steel instead of rubber elastomers. The only rubber components are high temperature O-rings.

Most downhole manufacturers get their power sections from a third party. The two most prominent manufacturers are Roper Pumps and R&M Energy Systems. Weatherford also manufactures power sections, but they are mostly for their own products. PV Fluids and Dyna Drill also manufacture power sections that are used in downhole motors. The former has a much greater range in sizes than the latter. It would seem that one of the limiting factors in designing a small downhole motor would depend on the size of the power sections available and the reliability and performance of these power sections. Roper Pumps currently manufactures a 1 1/2 – in. power section for their drilling motors and for their customers. Roper Pumps has also manufactured a 1.2-in motor for a client in East Texas. Currently there is no literature available on this motor. R&M Energy manufactures a power section as small as 1 11/16-in. power section for its clients. Weatherford currently manufactures a 1-11/16-in. power section for its downhole motors. PV Fluids manufactures a power section as small as 2-1/16 in. for its clients.

As a side note, there is difference between the MacDrill power section (manufactured for Weatherford by Rotech) and the power sections normally associated with PDMs. The MacDrill uses a vane turbine, which operates concentrically with little friction and heat byproducts. A PDM is based on eccentric operation with heat generated from friction between the rotor and stator.

3.1.5 Companies that Manufacture Downhole Drilling Motors

There are currently a number of companies that manufacture small downhole motors. To date, twenty-six companies have been identified that manufacture downhole motors or power sections for downhole motors capable of drilling and thru-tubing operations of 3 in. or less. The list of companies is provided in Table 3.1.

Table 3.1 Companies that Manufacture Downhole Drilling Motors

Company Name	Power Section/Motor Manufacturer	Sizes of Motors/Power Sections Provided (OD)	Types of Motors (media)
Advanced Coiled Tubing	Motors	Uncertain	Uncertain
Bico Drilling Tools Inc.	Motors	1-11/16 in. – 11-1/4 in.	Air and Hydraulic
Baker Hughes INTEQ	Motors	1-11/16 in. to 12-3/4 in.	Air and Hydraulic
Canadian Advanced Inc.	Motor s	3-1/2 in. – 8-5/8 in.	Electric
Cavo Drilling Motors	Motors	2-7/8 in. – 9-5/8 in.	Air and Hydraulic
Directional Drilling Contractors	Motors	3-in. -	Hydraulic
Dyna Drill	Power Sections	2-7/8 in. – 11-1/4 in.	Air and Hydraulic
Grifco, Inc.	Motors	Uncertain	Uncertain
Griffith-Vector (National Oilwell Subsidiary)	Motors	1-11/16 in. – 3-1/8 in.	Air and Hydraulic
Horizontal Technology Inc.	Motors	2-7/8 in. – 7-3/4 in.	Air and Hydraulic
Inrock	Motors	2-7/8 in. – 8 in	Air and Hydraulic
International Directional Services	Motors	1-11/16 in. – 11-1/4 in.	Air and Hydraulic
NQL Drilling Products	Motors	1-11/16 in. – 11-1/16 in.	Air and Hydraulic
PV Fluid Products	Power Sections	2-1/16 in. – 11-1/16 in.	Air and Hydraulic
R&M Energy	Power Sections	1-11/16 in. – 11-1/4 in.	Air and Hydraulic

Systems			
Roper Pumps	Power Sections and Motors	1-1/2 in. – 12-3/4 in.	Air and Hydraulic
Rotech Group	Power Sections and Motors	1-11/16 in. – 4-3/4 in.	Air and Hydraulic
Ryan Energy Technologies	Motors	3-1/2 in. – 9-5/8 in.	Air and Hydraulic
Schlumberger	Motors	1-11/16 in. – 2-9/16 in.	Air and Hydraulic
Sharewell Directional Drilling	Motors	2-7/8 in. – 6-3/4 in.	Air and Hydraulic
Slimhole International Drilling	Motors	1-1/2 in. – 11-3/4 in.	Air and Hydraulic
Sperry Sun	Motors	1-3/4 in. – 11-1/4 in.	Air and Hydraulic
Thru Tubing Solutions	Motors	1-11/16 in. – 2-7/8 in.	Hydraulic
Weatherford International Ltd.	Motors	1-11/16 in. – 3-1/2 in.	Air and Hydraulic
Wenzel Downhole Tools	Motors	2-7/8 in. – 9-5/8 in.	Air and Hydraulic
XL Technology	Motors	3-1/8 in.	Electric

3.1.6 Individual Companies with Brief Summary Description

Advanced Coil Tubing – Unable to contact Advanced Coil Tubing via phone or email. Based on their website they have CT units as small as 1-3/4 in. They may be involved in downhole motor manufacturing, but could not verify if they are still in business.

Bico Drilling Tools Inc. - Bico Drilling Tools, Inc. is an international company that designs, manufactures and services downhole drilling motors and other drilling tools for the oilfield, mining, and trenchless construction industries. Bico has over 40 basic motor configurations available ranging in size from 1-11/16 in. to 11-1/4 in. OD. Their main product motor line is the Flex Drill Motor. The Flex Drill Motor has sizes ranging from 1-11/16 in. to 2-7/8 in. These are all hydraulic PDMs.

Baker Hughes INTEQ - Baker Hughes INTEQ delivers advanced drilling technologies and services that deliver efficiency and precise well placement. Major capabilities include directional drilling, measurement-while-drilling (MWD), logging-while-drilling (LWD), drilling fluids, coring systems and well-site information management services. Baker Hughes INTEQ manufactures the line of Navi-Drill Ultra downhole motors and are available in a large variety of configurations, covering the entire operational envelope in sizes from 1-11/16" up to 12-3/4". They are available in various versions for high torque and high-speed applications to show their premium reliability in combination with all types of bits. Temperature ratings range from 265° F to 190°C (375°F).

Canadian Advanced Inc. – Canadian Advanced Inc. supplies all equipment and services associated with electric submersible pumps. Canadian Advanced Inc. manufactures electric motors ranging in size from 4-1/2 in. to 8-5/8 in. They are the only electric motor manufacturer identified in Canada.

Cavo Drilling Motors – Cavo Drilling Motors range in size from 2-7/8 in. to 9-5/8-in.. The single drilling motor under 3-in. is a 2-7/8 in. hydraulic PDM.

Directional Drilling Contractors – DDC is involved in innovation, design, and implementation of oilfield tools. They are involved in directional and horizontal drilling, to MWD Steering Tool and Gyro Services. DDC has downhole motors starting in size from 3-in diameter. These are all hydraulic PDMs.

Dyna Drill – Dyna Drill manufactures power sections for downhole motors for the petroleum industry. Dyna Drill manufactures power sections ranging in size from 2-7/8 in. to 11-¼ in.

Grifco, Inc. – Grifco once manufactured downhole motors. They manufactured a downhole motor as small as 1-½ in. Currently unable to determine if they are still in business, have been bought out, or are out of business.

Griffith-Vector (National Oilwell Subsidiary) - Griffith-Vector, a subsidiary of National Oilwell, manufactures a wide range of innovative downhole tools for the coiled tubing market. They provide custom designed solutions to the end products to support coiled tubing operations. Griffith-Vector offers two types of motor head assemblies, a high torque drilling motor-head assembly, and a heavy-duty motor-head assembly. Both motor head assemblies range in size from 1 11/16-in. – 3-1/8 in. OD. All motor head assemblies are hydraulic in nature.

Horizontal Technology Inc. – Horizontal Technology Inc. offers downhole motors and their component parts. Horizontal Technology Inc. offers downhole motors under the Vector/Trudrill line. The motors range in starting size from 2-7/8 in. to 7-3/4 in.

Inrock – Inrock is a supplier of drilling tools, equipment, products and services. Inrock supplies directional drilling motors ranging in size from 2-7/8 in. to 8-in. OD.

International Directional Services – International Directional Services is a leading supplier of services, rentals and sales of tools for directional drilling services, directional borehole surveying, oriented core and directional project planning consulting for the Mining Industry, Geotechnical and Environmental fields. International Directional Services manufactures the Accu-Dril Line of downhole motors. The motors range in starting size from 1-11/16 in. to 11-1/4 in.

NQL Drilling Products – NQL Drilling Tools is the provider of Black Max positive displacement motors for downhole drilling. Black Max comes in over 80 configurations of PDMs ranging in size from 1-11/16 O.D. to 11-1/4 O.D. The motor configurations are

made of standard nitrile, highly saturated nitrile, and hot hole (oversized stator). Power sections can be run with water and oil-based mud, air nitrogen, foam, mist and water. Power sections are purchased from a third party supplier, as they are by most downhole motor manufacturers.

PV Fluid Products – PV Fluid Products is a supplier of power sections to the oil and gas industry. They specialize in the design, supply and support of mud motors used in down-hole horizontal and directional drilling. PV Fluid Products manufactures power sections ranging in size from 2-1/16-in. to 11-1/4 in. OD.

R&M Energy Systems – R&M Energy Systems supplies power sections for horizontal and directional drilling applications, downhole pumps for crude oil recovery and gas well dewatering, tubing wearing solutions, wellhead equipment and closure products. R&M Energy Systems produces power sections under the Moyno Power Section brand name. Moyno comes in over 50 standard, non-proprietary power sections ranging in size from 1-11/16-in. to 11-1/4 in. OD. Moyno also produces power sections for compressible fluids such as air and gas starting in sizes of 2.88-in., short radius power sections also starting at 2.88 in. and other specialty power sections.

Roper Pumps – Roper Pump Company produces power sections and PDMs for directional, horizontal and vertical drilling applications. Roper power sections come in a number of standard configurations that range in size starting at 1-1/2 in. OD to 12-3/4 in. OD. Roper also produces power sections for compressible fluids such as air/foam that start in sizes of 1-11/16 in. as well as specialty power sections of various sizes.

Rotech Group – The Rotech Group is an independently owned group of companies based in Aberdeen, Scotland. Rotech Engineering which is one of the three operating divisions within the Rotech Group specializes in the development of innovative drilling tools for the Oil and Gas and Geothermal markets. There particular areas of expertise are High Temperature, Underbalanced Drilling and Short Radius operations. Rotech manufactures the MacDrill line of motors (including power sections) that is exclusively licensed to Weatherford. The MacDrill motor ranges in size from 1-11/16 in. to 4-3/4 in.

Ryan Energy Technologies – Ryan provides horizontal and directional drilling technology and services. Ryan creates fit-for-purpose technology for horizontal and directional drilling. Ryan manufactures PDMs that range in size from 3-1/2 in. OD to 9-5/8 in. OD.

Schlumberger – Schlumberger is a global oilfield and information services company comprising three primary business segments. Schlumberger manufactures a motorhead assembly ranging in size from 1-11/16 in. to 2-9/16 in. Schlumberger more than likely manufactures another line of motors, but we were unable to find someone to discuss the motor line.

Sharewell Directional Drilling – Sharewell Directional Drilling is a leading supplier of downhole drilling tools, guidance systems and services for the horizontal drilling

industry. Sharewell Directional Drilling manufactures PDMs ranging in sizes from 2-7/8 in. to 6-3/4 in. OD.

Slimhole International Drilling – Slimhole International Drilling maintains a comprehensive inventory of equipment and services dedicated to horizontal directional drilling. SlimDril provides motors ranging in size from 1-1/2 in. to 11-3/4 in. OD. A third party supplier manufactures the power sections used in their downhole motors.

Sperry Sun – Sperry Sun provides a wide range of energy-related drilling expertise, technology and services worldwide. Sperry Sun develops a wide range of positive displacement motors under the Sperry Drill® line. Sizes of the air and hydraulic motors ranges from 1-3/4 in. to 11-1/4 in. OD.

Thru Tubing Solutions – Thru Tubing Solutions is involved in the coiled tubing and snubbing industry. They provide service to the oilfield industry, specializing in working downhole tools under pressure during various fishing and drilling operations. Thru Tubing Solutions manufactures the Titan Motor line of PDMs. Sizes of the hydraulic motors ranges from 1-11/16 in. to 2-7/8 in. OD.

Weatherford International Ltd. – Weatherford International Ltd. is an oilfield services company focusing on drilling and cementing products, well installation and intervention services, and compression products and services. Weatherford manufactures a number of different PDMs. Their high performance line ranges in size from 1-11/16 in. OD to 3-1/2 in. OD. Rotech manufactures the MacDrill High Temperature Motor line exclusively for Weatherford for operation up to 500 ºC, ranging in size from 1-11/16 in. OD to 4-3/4 in. OD. They are also one of the few companies that manufacture power sections for its own products.

Wenzel Downhole Tools – Wenzel Downhole Tools is a supplier of downhole drilling tools to the oil and gas industry. Wenzel Downhole Tools manufactures PDMs ranging in size from 2-7/8 in. to 9-5/8 in. OD.

XL Technology – XL Technology designs, manufactures and markets innovative oilfield service equipment, with particular emphasis on coiled tubing technology. XL Technology is currently testing an electric downhole motor. The smallest electric downhole motor they are currently testing is a 3-1/8 in. OD motor.

3.2 Ultra High Speed Drilling Bits

Ultra High Speed Drilling is an area of research that may offer significant benefits to the microhole initiative, including faster penetration rates at lower weight-on-bits and reduced environmental footprints. Very little information was found related to ultra-high speed drilling bits up to 50,000-rpm. Currently only one company, Terra Tek, has been identified as pursuing any research and development in ultra-high speed drilling. The research they are pursuing is part of the DOE Ultra High Speed Drilling Program. Similar

in concept to high-speed dental drills, the R&D work is looking into using electric motors to power natural diamond coring bits of less than 1-in. at speeds of up to 50,000 rpm. As part of Ultra High Speed Drilling feasibility analysis, Terra Tek has demonstrated that ultra high speed drilling could achieve higher rates of penetration with lower weight-on-bit in a variety of rock types – sandstone, limestone and basalt. If the R&D work proves feasible in the laboratory, the next step will be to prove its feasibility in more practical applications. But based on information available, there is nothing currently existing that will address ultra high speed drilling and more R&D will be needed in this area.

4.0 Industry Experts / Key Knowledgeable Persons

Baker Oil Tools	
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Title or Position	Senior Applications Advisor
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5.0 Summary and Conclusions

As a result of various data searches of the internet, trade publications and trade journals, as well as follow up discussions with downhole motor manufacturers and CT service providers, a total of twenty-six companies were identified that are involved in the manufacture of small downhole motors and power sections of at least 3-½ in. OD or smaller. Twenty-three companies were identified that manufacture downhole motors in sizes of specific interest to the microhole solicitation. Five companies were identified that manufacture power sections for these small downhole motors. The smallest downhole motor that has been identified that is in use in the petroleum industry is 1.2-in. hydraulic downhole motor used for scraping the inside lining of pipe. A 1-½ in. downhole motor is manufactured that is slightly more prevalent in the petroleum industry. This too is a hydraulic motor and is used strictly for cleaning and scraping. The smallest downhole motor that is used extensively within the petroleum industry is the 1-11/16 in. downhole motor that is commonly used in thru tubing operations. Downhole motors that run on both compressible and incompressible fluids in this size have been manufactured. The smallest electric downhole motor that has been manufactured is 3-1/8 in. A smaller one could possibly be manufactured.

No obvious technological limitations have been identified for manufacturing a downhole motor smaller than 1.2-in. A number of downhole motor manufacturers have stated they can build downhole motors as small as a 1-in. and possibly even smaller. Power section manufacturers have also stated that there is no technological limit to manufacturing the rotors and stators necessary for the power section for such small downhole motors. Small diameter downhole motors for the petroleum industry have been used for well

interventions and laterals. CT has been successfully used in sidetracking high angle/horizontal wells through production liners of wells on the North Slope of Alaska. The horizontal sections of some of these sidetracks have ranged from 1,000 to 2,000 ft-md. The hole sizes drilled range from 2-3/4 in. to 4-1/8 in (Reference #16). The success of these commercially available downhole motors for drilling shallow wells down to 5000-ft is uncertain. Some industry people feel that existing off the shelf 2-7/8 in. downhole motors and possibly 2-3/8 in. downhole motors could successfully be used to do "grass roots" drilling down to 5000-ft in depth. Some CT units are currently in use for drilling shallow wells in Canada. The CT units are capable of drilling 4000-ft wells complete with 5-1/2 in. casing. Deeper wells have been completed with 4-1/2 in. casing (Reference #19). LANL has performed a significant amount of work with small downhole motors, including the testing of a number of commercially available downhole motors. They were considered sufficient for drilling in soft formations but insufficient for drilling in harder formations. LANL expects further research and development will need to be undertaken to make them conducive for drilling production wells.

There is no current industry need that has been identified to improve on the capabilities of small downhole motors. There is no driving force to build downhole motors smaller than 1-11/16 in. and no industry need to make them robust enough to drill a production well. Any improvements being done to small downhole motors are to improve their performance or versatility. For hydraulic motors these improvements include ability to work in higher temperature environments, working with a greater variety of drilling fluids or shortening motor length. For air motors this includes improving torque output and cuttings removal. Electric motors are still currently in their testing phase. There is no R&D work that has been identified at the university or national lab level in regards to downhole motor work. There has been some work done in the past at the university level, but as mentioned previously there has been no industry or government support to fund new research and development on small downhole motors.

Very little information was found related to ultra-high speed drilling bits up to 50,000 rpm. Only one company was found that is doing work in this area. They are looking into using electric motors to power natural diamond coring bits of less than 1-in. at speeds of up to 50,000 rpm. It is still in its beginning stages, so it is difficult to comment on the results or success of this work. If it proves feasible in the laboratory, the next step will be to show it has practical application; otherwise there is nothing available that is capable of ultra-high speed drilling, and further R&D will be needed.

Acknowledgements
The author would like to thank Jim Thomson from Los Alamos National Laboratory for his review and comments during the writing of this paper.

6.0 References

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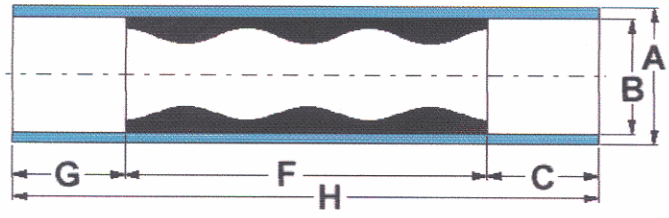
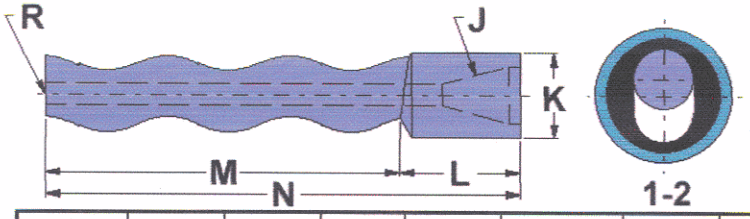
7.0 Attachments

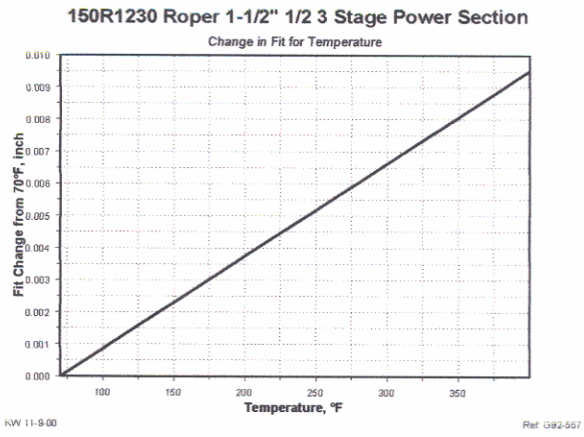
1. Technical Specs for 1-1/2 in. 3 Stage Power Section manufactured by Roper Pumps.
2. Technical Specs for 2-3/8 in. 5:6 Power Section manufactured by R&M Energy Systems.
3. Technical Specs for 1-11/16 in. 1:2, 3 Stage Black Max Motor.
4. Technical Specs for 1-11/16 in. 5:6, 2.5 Stage Flex Drill Motor manufactured by Bico Drilling
5. Technical Specs for 1-11/16 in. MacDrill Motor manufactured for Weatherford
6. Technical Specs for 1-11/16 in. to 2 7/8 in. Navi-Drill X-treme Workover Motor manufactured by Baker Oil Tools

1-1/2” 1/2 3 STAGE

150R1230





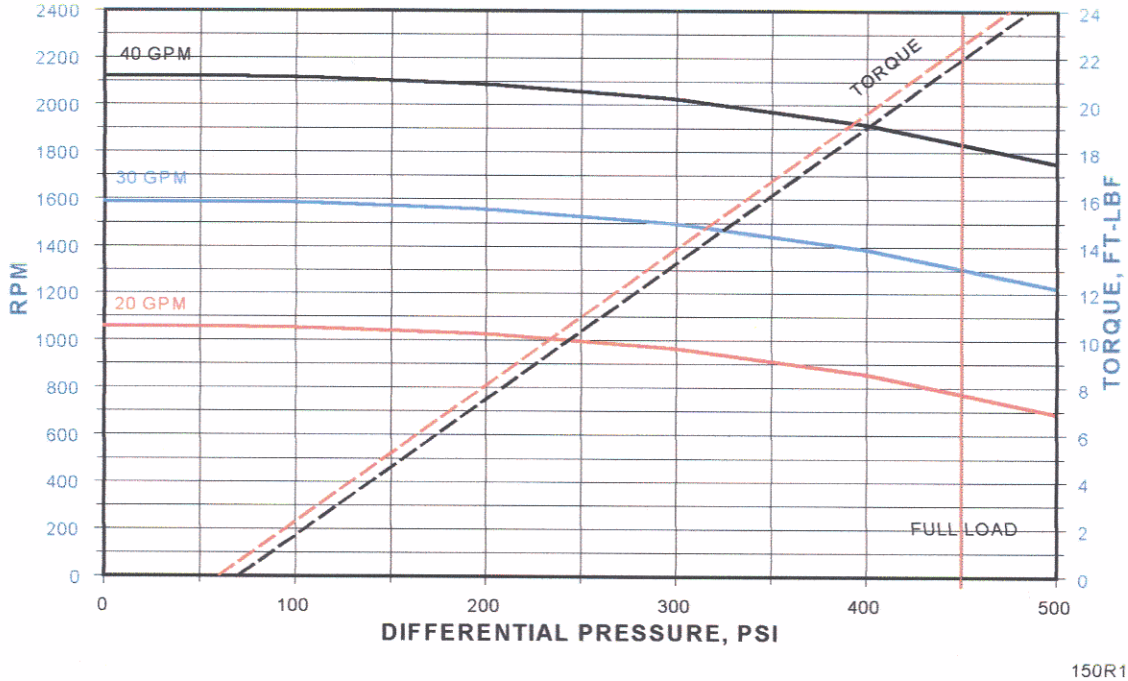


A	B*	C	F	G	H	M	N	L	K	R*	J*
1-1/2	1-1/4	4	40	14	58	41	45	4	7/8	—	—

	STD
STATOR MAJOR DIAMETER	1.172
STATOR MINOR DIAMETER	0.576
ROTOR MAJOR DIAMETER	0.878

APPROX STALL TORQUE	50 FT-LBF
ROTOR ECCENTRICITY	.149
ROTOR WEIGHT	7 LBS.
STATOR WEIGHT	10 LBS.

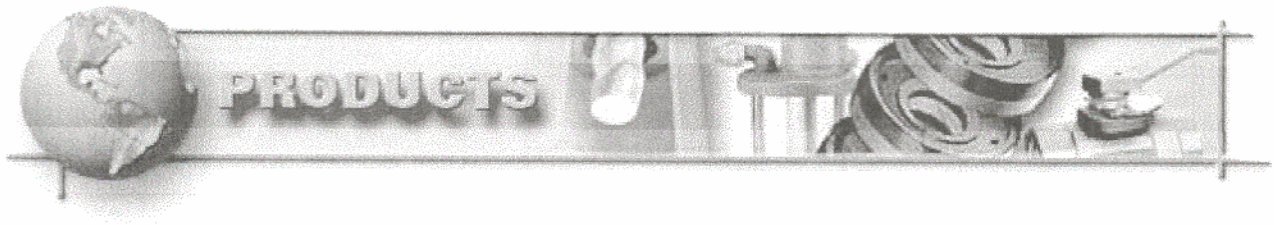
PERFORMANCE DATA



150R1230

ROPER PUMPS

*Threads, centers, and other features used for manufacturing are not shown. Please ask for details.



Moyno® Power Section - Slim Hole/Coiled Tubing Models [238M5625]

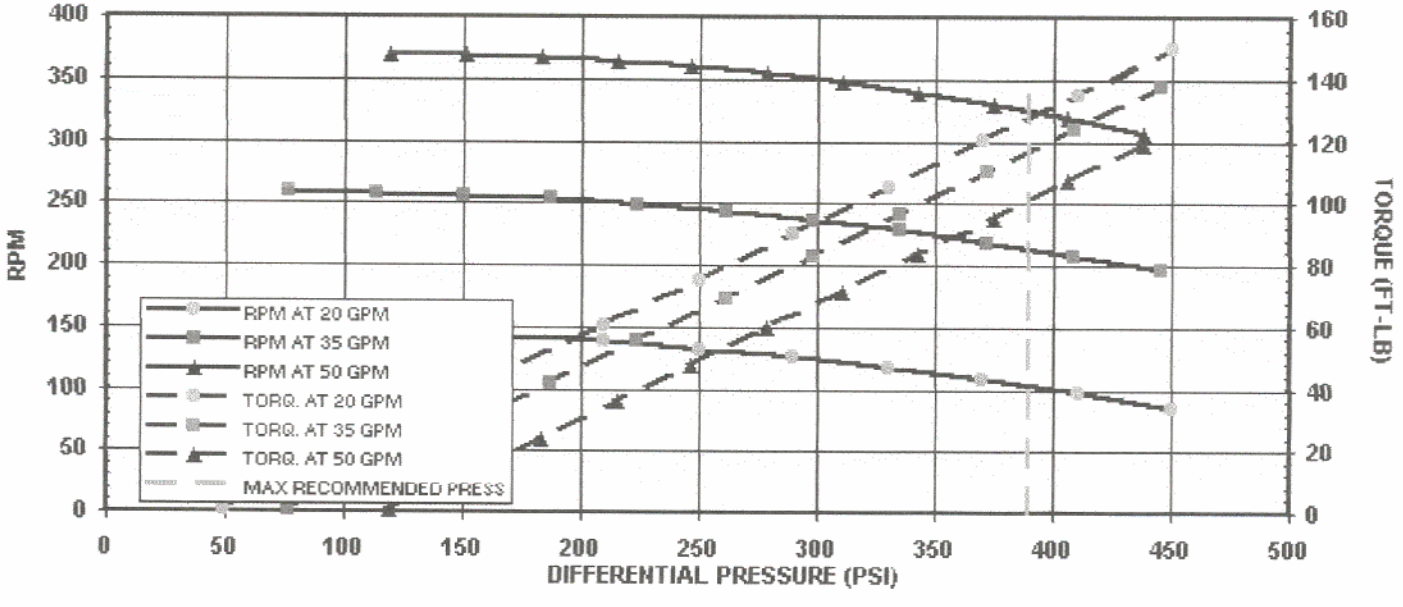
Performance

Model	Displ (Gal/Rot)	Flow (GPM)	Speed (RPM)	Press (PSI)	Full Load Torque (Ft-Lbs)	Lobe Config	No of Stages
238M5625	0.13	20-50	160-400	385	115	5:6	2.5

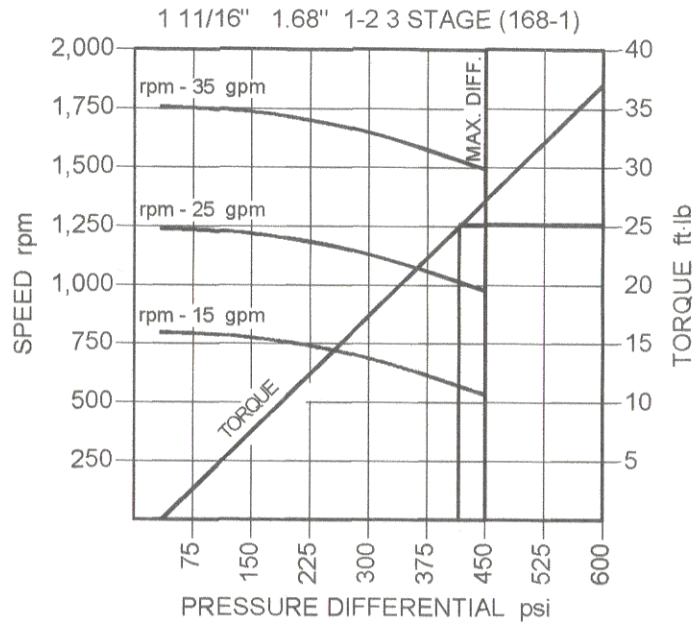
Dimensions (Inches)

Model	Rotor Box Thread	Rotor Overal Length	Stator OD	Stator ID	Stator Overal Length
238M55625	3/4-10 UNC-2B	51.50	2.38	1.88	58.50

Performance Curves



Stator Configuration	1 11/16" 1.68" 1-2, 3 Stage	
Bearing Assembly	**1 11/16"**	**43 mm**
Volume	15-35 gpm	57-133 lpm
Speed	534-1,756 rpm	
Torque	25 ft-lb	34 N *m
Max. Pressure Drop	1,500 psi	10,342 kPa
Max. Diff. Pressure	450 psi	3,103 kPa
Bit To Bend Length	22"	559 mm
O/A Length	86"	2,184 mm
Hole Size	1 7/8"-3"	48-76 mm
Top Connection	AW-ROD	
Bottom Connection	AW-ROD	
Bearing Load (compression)	dynamic=2,500 lb	1,110 daN
	static=6,000 lb	2,670 daN
Bearing Load (tension)	dynamic=2,500 lb	1,110 daN
	static=6,000 lb	2,670 daN
Max. Overpull (for re-runs)	6,000 lb	2,670 daN
Absolute Overpull	28,000 lb	12,455 daN



Volume (gpm)	Speed (rpm)	Torque (ft-lb)	hp
15	534-797	25	2.5
25	976-1,238	25	4.6
35	1,492-1,756	25	7.1

BICO DRILLING TOOLS, INC.

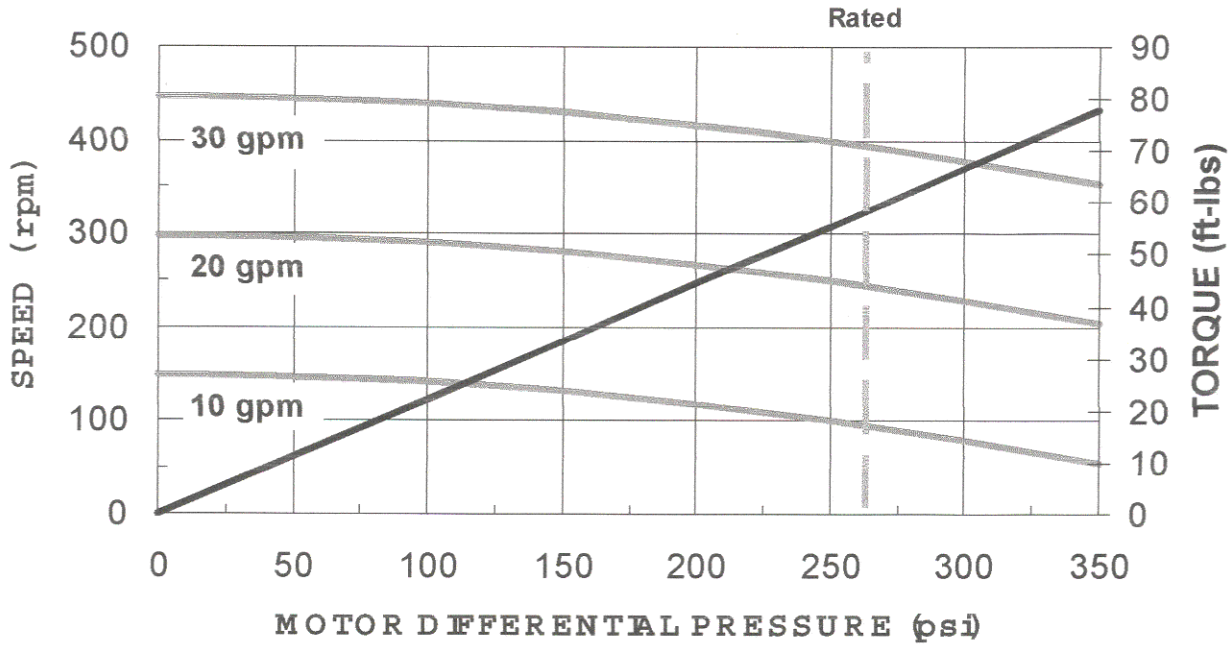
3040 Greens Road
Houston, TX 77032

Phone: (281) 590-6966
Fax: (281) 590-2280
eMail: sales@BICODrilling.com

1-11/16" P150 FLEX DRILL

Motor Specifications

Operating Data			
Flow Range		gpm (lpm)	10 - 30 (38 - 115)
Motor Pressure		psi (bar)	265 (18)
Bit Speed		rpm	90 - 390
Torque		ft-lbs (Nm)	60 (81)
Power		HP (Kw)	4.5 (3.3)
Physical Data			
Power Section		Stages	2.5
Configuration		Lobes	5/6
Overall Motor Length		ft (m)	7.5 (2.3)
Weight		lbs (kg)	40 (18)
Connections	Standard	Box	NC12, Top and Bottom
	Optional	Box	Available upon request
Bit Size		in (mm)	1-7/8 to 2-3/4 (47.6 - 69.9)



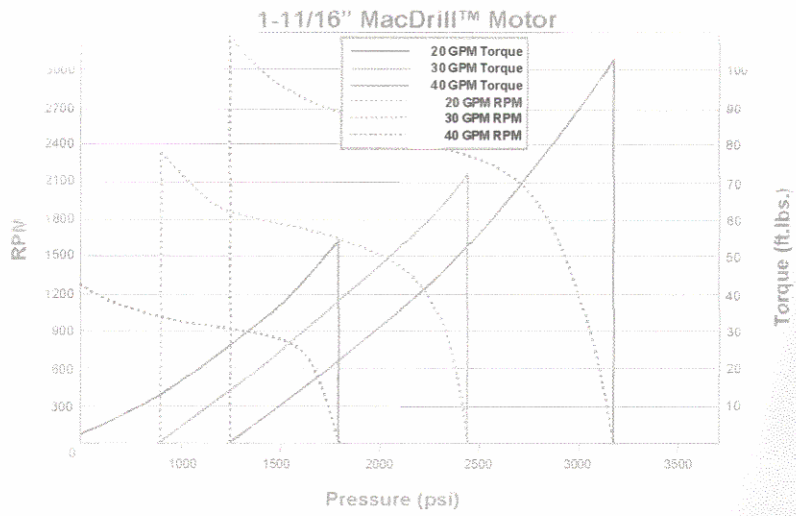
Specifications

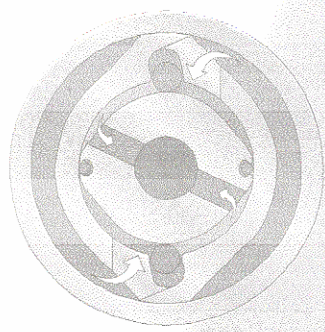
Equipment

Outside Diameter	1.688"
Overall Length	58.06"
Weight	26 lbs.
Connections	1" AMMT
Make-Up Torque	399 ft./lbs.
Bit Size Range	1.81" to 2.38"

Operational

Maximum Torque Output	95 ft./lbs.
Maximum Bit Pressure Drop	1,500 psi
Minimum Flow Rate	15 gpm
Maximum Flow Rate	40 gpm
RPM Range	1,500 to 2,800
Maximum Weight on Bit	7,920 lbs.
Maximum Temperature	500°F
Maximum Overpull	12,000 lbs.





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Phone: 713-693-4000
Fax: 713-693-4300
www.weatherford.com

Navi-Drill X-treme™ Workover Motor
Product Family No. H13283

OPERATING SPECIFICATIONS:

OD		Power	Standard	Length		Flow		Speed	Op. ΔP ■		Op. Torque ■		Temperature	
In.	mm	Section	Connection	ft	m	GPM	LPM	RPM	psi	bar	ft-lbs	Nm	°F	°C
1.69	42.9	XS	1" AMMT	5.52	1.68	50	189	640	435	30	75	100	400	204
		X		7.64	2.33				870	60	150	200		
		AD		8.33	2.54	40	151	350	725	50	180	245		
2.13	54.1	XS	1-1/2" AMMT	5.95	1.81	65	246	600	580	40	105	140		
		X		8.17	2.49				1015	70	250	340		
		AD		9.54	2.91	45	170	300			350	475		
2.88	73.2	XS	2-3/8" Reg or 2-3/8" PAC DSI	7.81	2.38	120	454	490	800	55	310	420		
		X		10.67	3.28				1,160	80	620	840		
		AD		12.58	3.83	85	322	250			885	1,200		

Note: XS = "Short" X = Std. Length (Mud) AD = Air Motor

■Operating pressure & operating torque are the maximum values the motor should be run at for continuous operation.

PEAK PERFORMANCE SPECIFICATIONS:

Tool OD		Power Section	Max Torque ■		Max ΔP ■		Stall Torque		Stall ΔP	
In.	mm		ft-lb	Nm	psi	bar	ft-lb	Nm	psi	bar
1.69	42.9	XS	95	130	545	37.5	115	155	655	45
		X	190	260	1090	75	230	310	1305	90
		AD	225	305	905	62.5	270	365	1090	75
2.13	54.1	XS	135	180	545	37.5	160	220	655	45
		X	315	425	1270	87.5	375	510	1525	105
		AD	440	595	1270	87.5	525	710	1525	105
2.88	73.2	XS	390	530	725	50	470	635	870	60
		X	830	1125	1450	100	935	1270	1740	120
		AD	1105	1500	1450	100	1330	1800	1740	120

■Maximum pressure & maximum torque are the maximum values the motor can be operated at for a short period of time, taking increased wear rates into account.